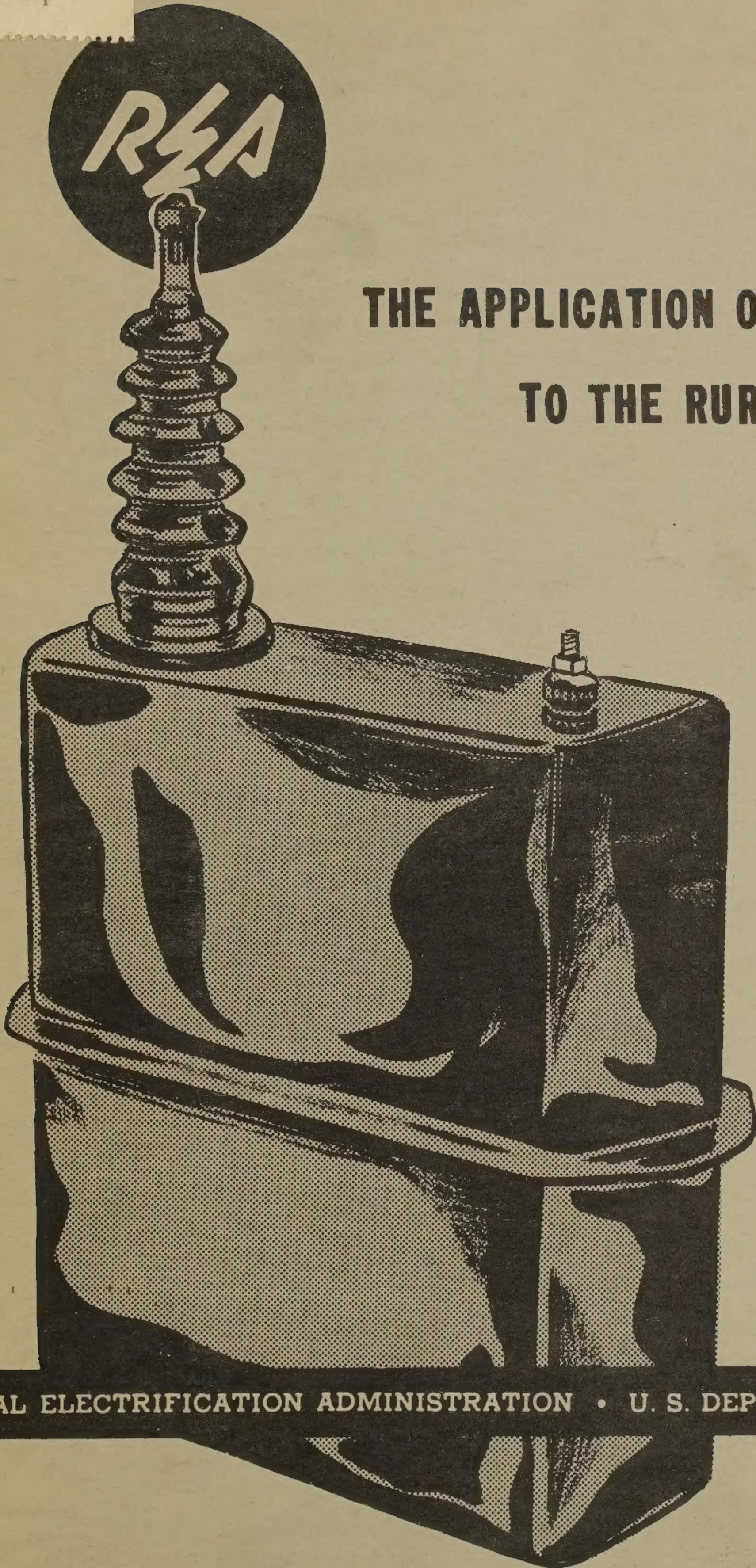


# THE APPLICATION OF SHUNT CAPACITORS TO THE RURAL ELECTRIC SYSTEM

RURAL ELECTRIFICATION ADMINISTRATION • U. S. DEPARTMENT OF AGRICULTURE

Usually, as a rural power distribution system matures, the system power factor declines; this results in increased energy losses, lower voltages at consumers' premises, poorer performance of energy utilization equipment and a greater cost per unit of energy delivered.

Shunt capacitors offer a means of improving the above conditions by reducing the reactive kilovar load carried by lines, transformers and generators.

Care must be used in choosing size and location of each individual capacitor installation in order to obtain the maximum benefits.

Capacitor installations may impose problems of increased inductive interference on nearby communication lines. However, corrective measures will usually eliminate such problems.

# THE APPLICATION OF SHUNT CAPACITORS TO THE RURAL ELECTRIC SYSTEM

April 1952

U. S. Department of Agriculture
Rural Electrification Administration
Technical Standards Division
Washington, D. C.

CONTENTS

# THE APPLICATION OF SHUNT CAPACITORS TO THE RURAL ELECTRIC SYSTEM

## I. INTRODUCTION

### A. GENERAL

The expansion of systems for farm electrification and the growth of motor and other inductive loads for home and farm uses is being accompanied by a downward trend in system power factors. Power factor penalty clauses in wholesale power contracts which caused no particular concern in the early operating period of a rural system assume increased importance as the system reaches maturity. This downward trend in power factors leads to power factor penalties in wholesale power contracts as well as increased system losses and voltage regulation problems. The shortage of capacity both in system and supply makes it necessary to explore possibilities for increasing their load capabilities. Approximately 17,000,000 kilovars of shunt capacitors, as a means of power factor correction, are now installed on power systems and in industrial plants.

At the present time, there is more need for power factor correction on 7.2/12.5-kv systems than on 14.4/24.9-kv systems. For this reason this manual is concerned chiefly with 7.2/12.5-kv wye-connected systems. However, the use of capacitors for 14.4/24.9-kv systems may bear consideration.

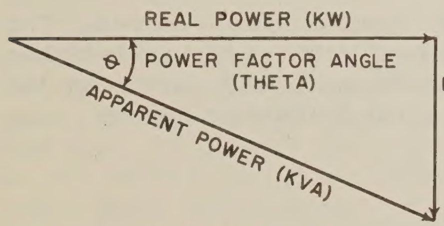



Figure 1. Lagging kilovars often form an appreciable component of the system load.

### B. LOAD COMPONENTS

The total power delivered by a distribution line to the load consists of two parts, as shown in figure 1. Figure 2 analogously illustrates the relation between kilovolt-amperes, kilowatts, kilovars and power factor. The real component, kilowatts (kw), does the work and the inductive component, lagging kilovars (kvar), is supplied to motors to magnetize the fields and to transformers to magnetize the cores. This reactive

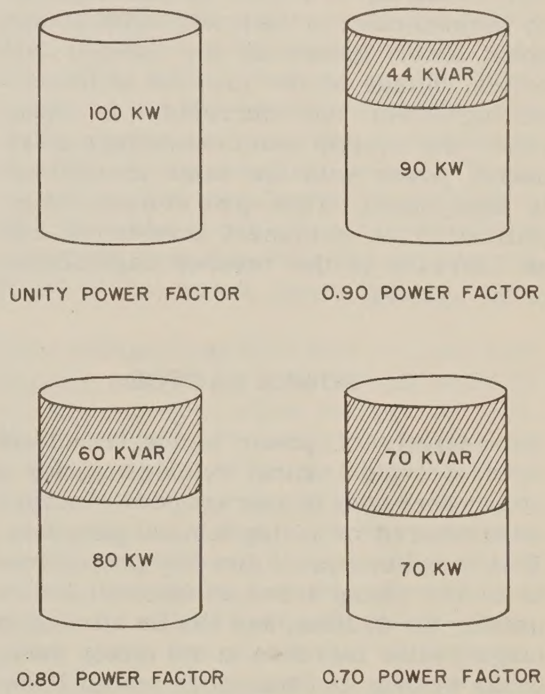



Figure 2. 100-kva loads at various power factors. At a given kilovolt-ampere load, with changing power factor, the reactive power increases more rapidly than the power factor decreases.

component performs none of the useful work, but must be furnished to these loads. The total power delivered to the load then consists of a real and a reactive component, and this total is measured in kilovolt-amperes, abbreviated as kva. The ratio of kw to kva is called the power factor. The reactive part of this total kva, while it performs no useful work, must be supplied by the generator at the power plant, transformed and transmitted, transformed again and delivered to the load which requires it. Therefore, the reactive part of the total kva delivered must travel through the entire system to be delivered to the load. If it can be canceled by a capacitive load placed at the load center of an aggregation of loads requiring inductive power, the system will be relieved of much of this burden. A capacitor may be thought of as a kilovar generator which supplies leading reactive power to the system. The resulting decrease in kva supplied by the generator at the power plant brings about lower losses in the system and better voltage at the load due to the resulting lower line currents. In many cases the system can then deliver more useful power with the same investment in equipment. This provides better utilization of equipment investment and an increase in the revenue capabilities of the system.

## C. POWER FACTOR

An analysis of power factor trends on several typical rural systems shows a steady decrease in average power factors as measured for billing demand purposes. This trend is almost directly proportional to the rising trend in kilowatt-hours used by the system, and can be attributed largely to the increase in the motor loads on the system as consumers install labor saving equipment for farmstead and household uses. Further analysis of the power factors on these systems indicates that the lower power factor can be attributed largely to automatic types of motor-driven devices which operate intermittently over a 24-hour period, such as refrigerators, home food freezers and water pumps. The load distribution of these devices is comparatively uniform over the daily load curve; consequently the load factor of the reactive component is very much higher than the load factor of the real component, since the real component does fluctuate widely over a 24-hour period. Figure 3 illustrates typical kilowatt and kilovar load curves. The kilowatt load factor on rural systems often averages 0.40, the kilovar load factor 0.70. A fairly constant kvar load factor simplifies the problem of power factor correction. If the power factor of such a system is corrected to unity at light load, it will be nearer unity at peak load.

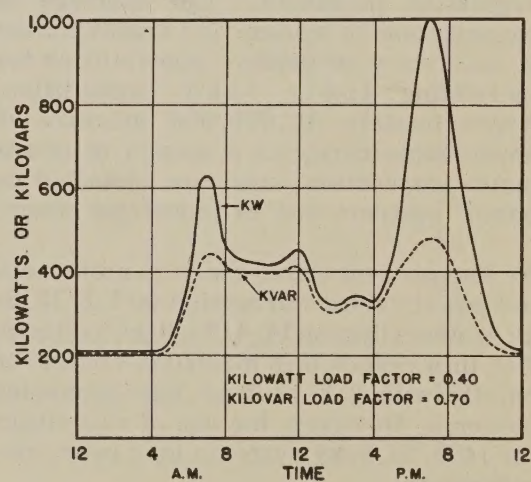



Figure 3. Sample load curves. The kilovar load factor is inherently higher than the kilowatt load factor on the typical rural distribution system.

# II DISCUSSION

## A. SIZE LIMIT

Surveys of annual load curves for several rural power systems show peak load power factors from 0.90 to 0.95 and minimum load power factors of 0.70; under the latter condition the kilowatt and kilovar loads are equal. Permanently connected, or unswitched capacitors may be installed on the system in amounts equaling the minimum kilowatt demand without causing leading power factors under light-load conditions. The ratio of minimum to peak annual kilowatt demand should be used as a guide in selecting the total capacitor kilovars to be installed. This ratio is often 0.20; in such a case, the capacitor kilovars required would amount to one-fifth the peak load kilowatt reading on the line under consideration.

## B. LOCATION

Generally the distribution of consumers on a rural system is such that, as the distance from the substation increases, the number of consumers per main line-mile of feeder increases. A permanently connected capacitor in such a primary circuit should be located at a distance from the substation of from one-half to two-thirds of the total length of the line, in order to obtain maximum benefits in voltage improvement and reduction of loss.

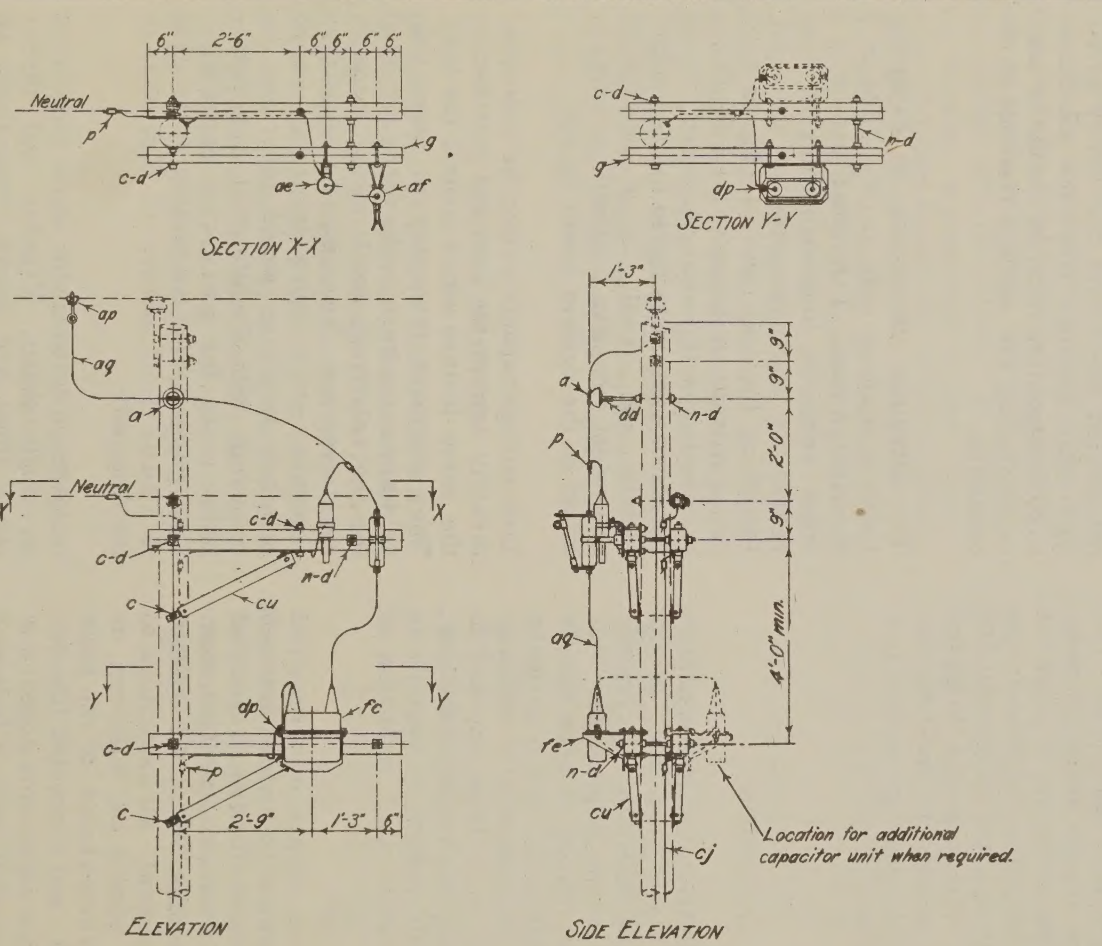
When more than one capacitor is required the capacitors should be divided between phases in proportion to the total connected distribution transformer capacity on each phase, as determined from the system load map. In general, all capacitors to be installed should be balanced on single-phase extensions of the main three-phase line, and connected line-to-neutral so that the correction appears in the substation as if it were a balanced Y-connected bank of capacitors. This balance must be maintained to avoid certain harmonic currents which would otherwise be produced in the neutral and may increase coordination problems with telephone circuits near the three-phase line.

Each phase should be treated separately as a system in itself, but the size of the total permanently connected capacitor installation for the three phases should not exceed the limits previously given. The total distance from the substation to each capacitor location should be used in computing the voltage rise due to the capacitor.

The foregoing discussion on capacitor location applies only in the case of a distributed load. Individual loads with a large reactive component may be corrected by the consumer at the load. Penalties for low power factor in such cases provide an incentive for consumers to install capacitors where needed. These capacitors are installed in the secondary circuit and result in a practically equivalent resistive load with no adverse effect on the system power factor.

Low-voltage capacitors may be connected directly across the load and switched by the same devices which control the load. They compare favorably in price with primary capacitors in the sizes required for the relatively small motor loads on rural systems. Secondary capacitors compare even more favorably where primary switching would otherwise be required, with the attendant high installation costs for primary capacitors. Load power factor correction in the case of induction motors is discussed in the Appendix.

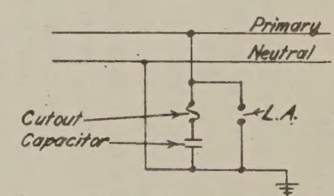
Installation drawings for shunt capacitors on single-phase, V-phase and three-phase lines are shown respectively on figures 4, 5 and 6. Care is necessary




| ITEM | NO. REQ. | MATERIAL | |
|---|---|---|---|
| a | 1 | Insulator, pin type | |
| c | 4 | Bolt, machine, 5/8" x req'd. length | |
| c | 4 | Bolt, machine, 1/2" x req'd. length | |
| d | 14 | Washer, 2 1/4" x 2 1/4" x 3/16", 13/16" hole | |
| d | 4 | Washer, round, 1 3/8" dia., 9/16" hole | |
| g | 4 | Crossarm, 3 3/4" x 4 3/4" x 5'-0" | |
| cu | 4 | Brace, crossarm, wood | |
| n | 3 | Bolt, double arming, 5/8" x req'd. length | |
| p | | Connectors, as req'd. | |
| ae | 1 | Lightning arrester | |
| af | 1 | Cutout, fuse, single shot, 15 K.V. | |
| ai | 1 | Rod, ground, 5/8" min. dia. | |
| aj | 1 | Clamp, ground rod | |
| al | | Staples, 3/16" x 1 1/2" x #9, as req'd. | |
| ap | 1 | Clamp, hot line, tap assembly | |
| aq | | Leads, #6 S.D. or equiv., as req'd. | |
| cj | | Ground wire, #6 S.D. or equiv. | |
| dd | 1 | Adapter, insulator | |
| dp | | Clamp, ground wire | * |
| fc | | Capacitor, ______ K.V.A. | * † |
| fe | | Hanger, capacitor, single unit | * |

* Specify number required.
† Specify K.V.A. required.

Note:
Not more than 30 K.V.A. should be connected to one fuse cutout.



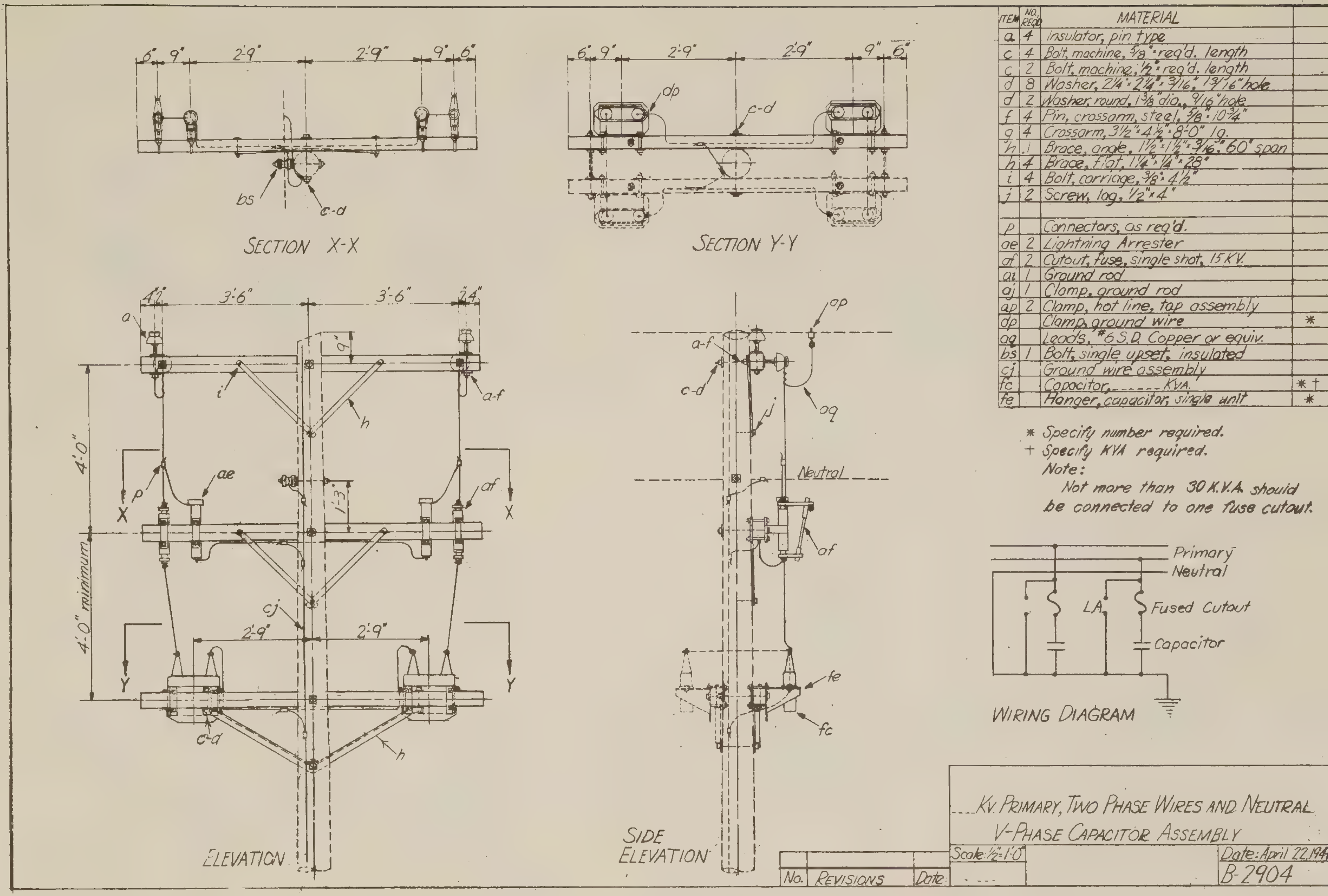

WIRING DIAGRAM

| No. | REVISION | DATE |
|---|---|---|

___ K.V. PRIMARY, 1-PHASE, 2-WIRE NEUTRAL GROUNDED
SINGLE PHASE CAPACITOR ASSEMBLY

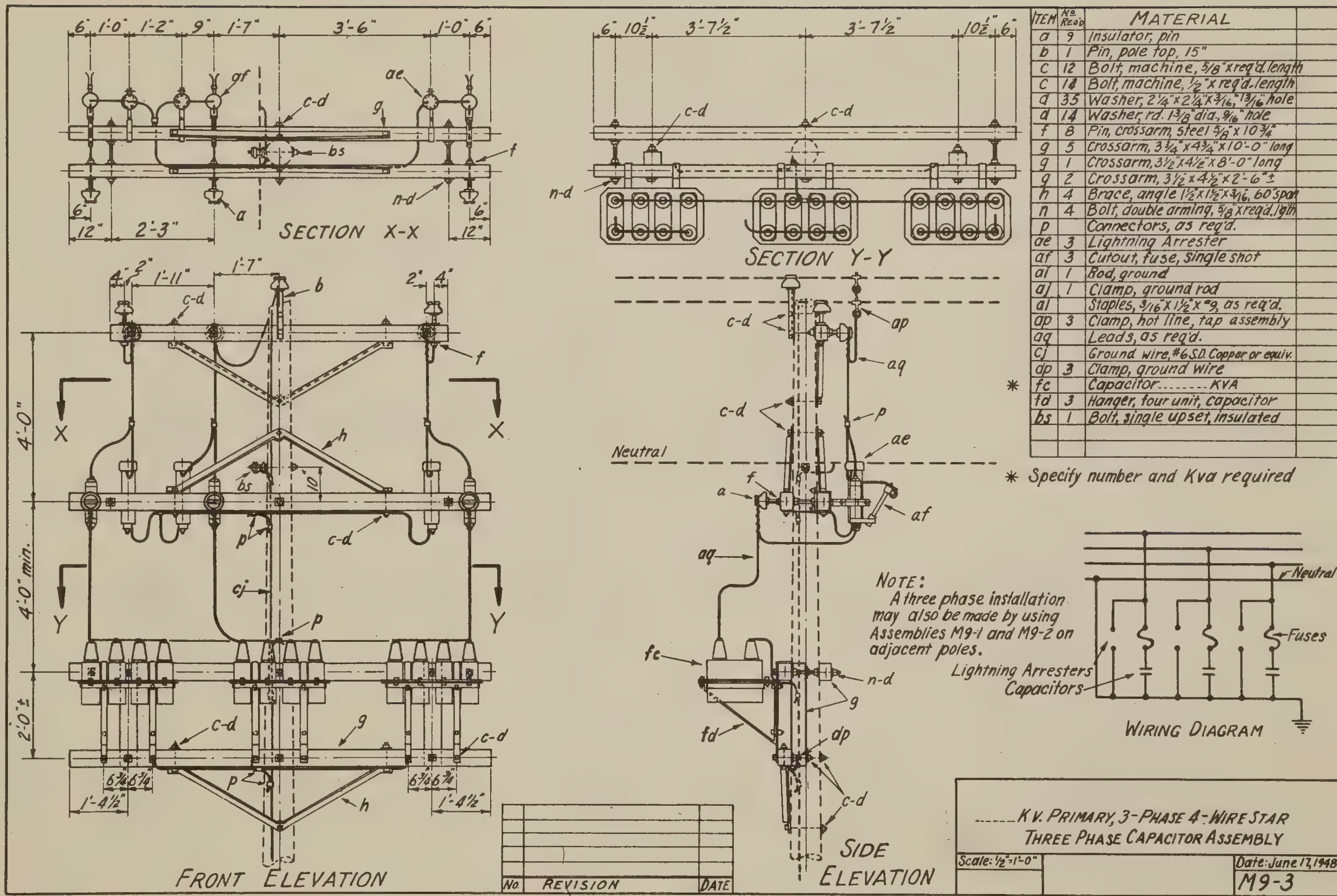
Scale: 1/2" = 1'0" | Date: April 5, '49
B2897

Figure 4



SECTION X-X
SECTION Y-Y
ELEVATION
SIDE ELEVATION
4'-0"
4'-0" minimum
3'-6"
2'-9"
1'-3"
Neutral
ITEM | NO. REQ'D | MATERIAL
a 4 Insulator, pin type
c 4 Bolt, machine, 5/8" x req'd. length
c 2 Bolt, machine, 1/2" x req'd. length
d 8 Washer, 2 1/4" x 2 1/4" x 3/16", 13/16" hole
d 2 Washer, round, 1 3/8 dia., 9/16 hole
f 4 Pin, crossarm, steel, 5/8" x 10 3/4"
g 4 Crossarm, 3 1/2" x 4 1/2" x 8'-0" lg.
h 1 Brace, angle, 1 1/2" x 1 1/2" x 3/16" x 60" span
h 4 Brace, flat, 1 1/4" x 1/4" x 28"
i 4 Bolt, carriage, 3/8" x 4 1/2"
j 2 Screw, lag, 1/2" x 4"
p Connectors, as req'd.
ae 2 Lightning Arrester
af 2 Cutout, fuse, single shot, 15 KV.
ai 1 Ground rod
aj 1 Clamp, ground rod
ap 2 Clamp, hot line, tap assembly
dp Clamp, ground wire *
aq Leads, #6 S.D. Copper or equiv.
bs 1 Bolt, single upset, insulated
cj Ground wire assembly
fc Capacitor, ____ KVA. * +
fe Hanger, capacitor, single unit *
* Specify number required.
+ Specify KVA required.
Note:
Not more than 30 K.V.A. should be connected to one fuse cutout.
Primary
Neutral
LA
Fused Cutout
Capacitor
WIRING DIAGRAM
No. REVISIONS Date
___ Kv. PRIMARY, TWO PHASE WIRES AND NEUTRAL
V-PHASE CAPACITOR ASSEMBLY
Scale: 1/2" = 1'-0"
Date: April 22, 194
B-2904


Figure 5




| ITEM | No. REQ'D | MATERIAL | |
|---|---|---|---|
| a | 9 | Insulator, pin | |
| b | 1 | Pin, pole top, 15" | |
| c | 12 | Bolt, machine, 5/8" x req'd. length | |
| c | 14 | Bolt, machine, ½" x req'd. length | |
| d | 35 | Washer, 2¼" x 2¼" x 3/16", 13/16" hole | |
| d | 14 | Washer, rd. 1 3/8" dia., 9/16" hole | |
| f | 8 | Pin, crossarm, steel 5/8" x 10¾" | |
| g | 5 | Crossarm, 3¾" x 4¾" x 10'-0" long | |
| g | 1 | Crossarm, 3½" x 4½" x 8'-0" long | |
| g | 2 | Crossarm, 3½" x 4½" x 2'-6" ± | |
| h | 4 | Brace, angle 1½" x 1½" x 3/16", 60" span | |
| n | 4 | Bolt, double arming, 5/8" x req'd. lgth | |
| p | | Connectors, as req'd. | |
| ae | 3 | Lightning Arrester | |
| af | 3 | Cutout, fuse, single shot | |
| al | 1 | Rod, ground | |
| aj | 1 | Clamp, ground rod | |
| al | | Staples, 3/16" x 1½" x #9, as req'd. | |
| ap | 3 | Clamp, hot line, tap assembly | |
| aq | | Leads, as req'd. | |
| cj | | Ground wire, #6 S.D. Copper or equiv. | |
| dp | 3 | Clamp, ground wire | |
| * fc | | Capacitor ........ KVA | |
| fd | 3 | Hanger, four unit, capacitor | |
| bs | 1 | Bolt, single upset, insulated | |
| | | | |
| | | | |

* Specify number and Kva required

Figure 6

in the installation of shunt capacitors on a V-phase feeder, in order to assure balanced voltages. Balanced voltages are obtained by the use of unequal amounts of capacitor kilovars on the two phases.[1]

### C. SWITCHED CAPACITORS

The following brief information on switched capacitors[2] is presented herein without a detailed description or cost data, for those who are familiar with permanently connected capacitors and are interested in attaining a higher power factor at heavy system loads. Generally the kilovars required to obtain this higher power factor are greater than the minimum kilowatt load on the system and, if permanently connected, would create a leading power factor at light load. In order to prevent this condition, it would be necessary to provide a means of switching the capacitors out of the circuit under light-load conditions. Switching under such conditions may have the following advantages:

1. Prevent overvoltage.
2. Reduce line current and resulting line losses.
3. Keep kilovolt-ampere demand low in proportion to kilowatt loading.
4. Keep power factor within desired limits.
5. Reduce substation transformer losses.

Choice of manual or automatic switching[3] depends upon the benefits expected, the size of the capacitor bank, the amount of variation of kilowatt and kilovar load over a typical load period and fluctuation of voltage with load. Manual switching requires an attendant to make the necessary observations of voltage, power factor and kilovar demand; therefore automatic switching would almost always be chosen, in preference to manual switching.

When automatic switching is chosen, the equipment required in addition to the capacitors and protective equipment includes the switching device and the control equipment.

The control equipment for automatic switching consists of a master element, a time delay device, and auxiliary devices such as an auto-manual switch and a close-trip switch. The master element is chosen to suit the conditions of the system on which it is to be used and may be actuated by voltage, current, kilovar, power factor or timing. In brief, the function of each of these types of master elements is as follows:

1. Voltage -- where objectionable voltage changes occur with varying loads. One type is essentially a contact-making voltmeter with range of adjustment from 90 to 110 percent, and a band width adjustable from three to seven and one-half percent. Another type incorporates a resistor inserted in series with a voltage regulating relay, which causes the relay to sense a lower voltage during high-load periods.
2. Current -- in response to changes in load current by means of a current sensitive relay. This means may be used on systems where the voltage is well regulated and the power factor of the load remains substantially constant with variation in kilowatt loading, or if the power factor of the circuit varies in a predictable manner with variation in kilowatt loading. The standard range of adjustment is 25 to 100 percent of the coil rating (5 amperes).
3. Kilovar -- used when load voltage is regulated and load power factor varies in an unpredictable manner with variation in kilowatt loading. This method uses an induction-type directional relay for single-phase indication, with adjustment from 3.3

[1]Numbered references are listed at the end of this publication.

amperes (66 percent) lagging to 1.6 amperes (32 percent) leading, with a band width adjustable from 2.5 to 0.7 amperes (50 to 14 percent). Kilovar control is rarely used, due to its cost.

4. Power-factor -- similar to a kilovar element in that it is usually an induction-type directional relay. A desensitizing control is required for this method to prevent hunting at light loads. This is due to the possibility of the band width being less than the change in signal caused by switching the capacitor. Power-factor control is rarely used, due to its cost.

5. Time-switching -- a simple device to switch capacitors at some predetermined time and usable only where the load characteristics are reasonably constant.

Switched capacitor installations may not be economically feasible except where larger loads permit the use of capacitors of 150-kvar rating or larger.

## D. PROTECTIVE EQUIPMENT[4]

Power circuits can remain in operation with part or all of a capacitor bank out of service. In the event of capacitor failure, it is desirable to isolate the failure from the power system and minimize the damage, with no interruption in service. The emphasis, therefore, is upon protection for the circuit instead of the capacitor.

### 1. Fuses

Fuse protection is necessary for each shunt capacitor installation mainly to disconnect a faulted capacitor from the line before the capacitor causes other current protective devices to operate. The fuse protection chosen must be coordinated with any line sectionalizing devices for the feeder being considered. The fuse must perform its function before the capacitor case bursts, in order to prevent personal injury or damage to adjacent equipment. Shunt capacitors are designed to operate satisfactorily at 135 percent of rated kilovars. This 35 percent of excess above nominal rating is to allow for kilovars due to excess voltage above nameplate fundamental frequency voltage; kilovars due to harmonic voltages in addition to the fundamental frequency voltage; and kilovars in excess of the nameplate kilovars due to manufacturing tolerances. Therefore the current protection device must have a nominal rating of more than 135 percent of the capacitor line current.

In general, the link should melt in 300 seconds at 150-300 percent rated current. Fuses for small capacitors should have at least a 5-ampere rating, to minimize the likelihood of fuse failure due to lightning or transient surges. The choice of fuse rating for a capacitor installation must be based on the fuse time-current characteristic, because of the wide variation in melting time-current characteristics between different types and makes of fuses.

### 2. Lightning Protection.

Lightning disturbances may cause damage to capacitors by bushing flashover or breakdown of the insulation between the internal elements and the case. Capacitor units connected line-to-neutral on a multi-grounded neutral system provide a low-impedance path for lightning surge current and some protection against overvoltage due to lightning. However, lightning damage under certain conditions may be incurred in spite of this inherent self-protection.

Lightning arresters are necessary, not only for protection of capacitors against lightning, but also for protection against transient overvoltages caused by switching operations, arcing grounds, disturbances caused by other arresters, and resonance or near resonance caused by motors while starting.

## E. SAFETY PRECAUTIONS

The same precautions with capacitor units are necessary as with other electrical equipment, when they are taken

out of service for repair or maintenance. In addition, a capacitor may retain a hazardous charge for an indefinite time after being disconnected. Generally discharge resistors are built into each capacitor unit which will reduce the terminal voltage of a unit to 50 volts or less in one minute, for units rated at 600 volts or less, and in five minutes for units rated higher than 600 volts.

It is not good practice to rely on these resistors to reduce terminal voltage of capacitors to a safe value when disconnected from line. After several minutes have elapsed during which time the discharge resistors should have reduced the capacitor terminal voltage practically to zero, the terminals should be simultaneously short-circuited and connected to ground, leaving such connections intact until work on the installation is completed. When the capacitors are removed from their racks, the terminals should be short-circuited and connected to their cases, due to their tendency to accumulate a residual charge if not short-circuited. The condition of the ground connection should be checked before work is done on the equipment.

## F. EFFECT ON SYSTEM PERFORMANCE

The energy loss[5] in a capacitor is very small, not exceeding 3.3 watts per kilovolt-ampere at rated voltage and frequency. Expressed in efficiency, this amounts to 99.67 percent. Capacitors energized at rated voltage always operate at full load; therefore system load cycles have no effect on the losses of capacitors operating at rated voltage.

1. Line Voltage.

The percent voltage rise in a line, due to a capacitor installation, is given as

$$\frac{\text{ckva} \times X \times d}{10\ \text{kv}^2}$$

where the symbols are as follows:

d = length of line, circuit-miles

ckva = total capacitor kva (single-phase and 3-phase lines)
= 1/2 total capacitor kva (V-phase line)

X = reactance, ohms per circuit-mile (single-phase and 3-phase lines)
= 1/2 single-phase reactance, ohms per circuit-mile (V-phase lines)

kv = line-to-ground kilovolts (single-phase and V-phase lines)
= line-to-line kilovolts (3-phase line)

Values of impedance for lines with multi-grounded neutral wire are given in reference 6. Figure 7 indicates percent voltage rise per mile on single-phase and three-phase lines.

2. Substation Transformer Voltage.

The percent voltage rise in a substation transformer bank at full load, due to a capacitor installation, is given by the following:

$$\frac{\text{ckva} \times Z}{\text{tkva}}$$

where Z = percent transformer impedance
tkva = transformer kva rating

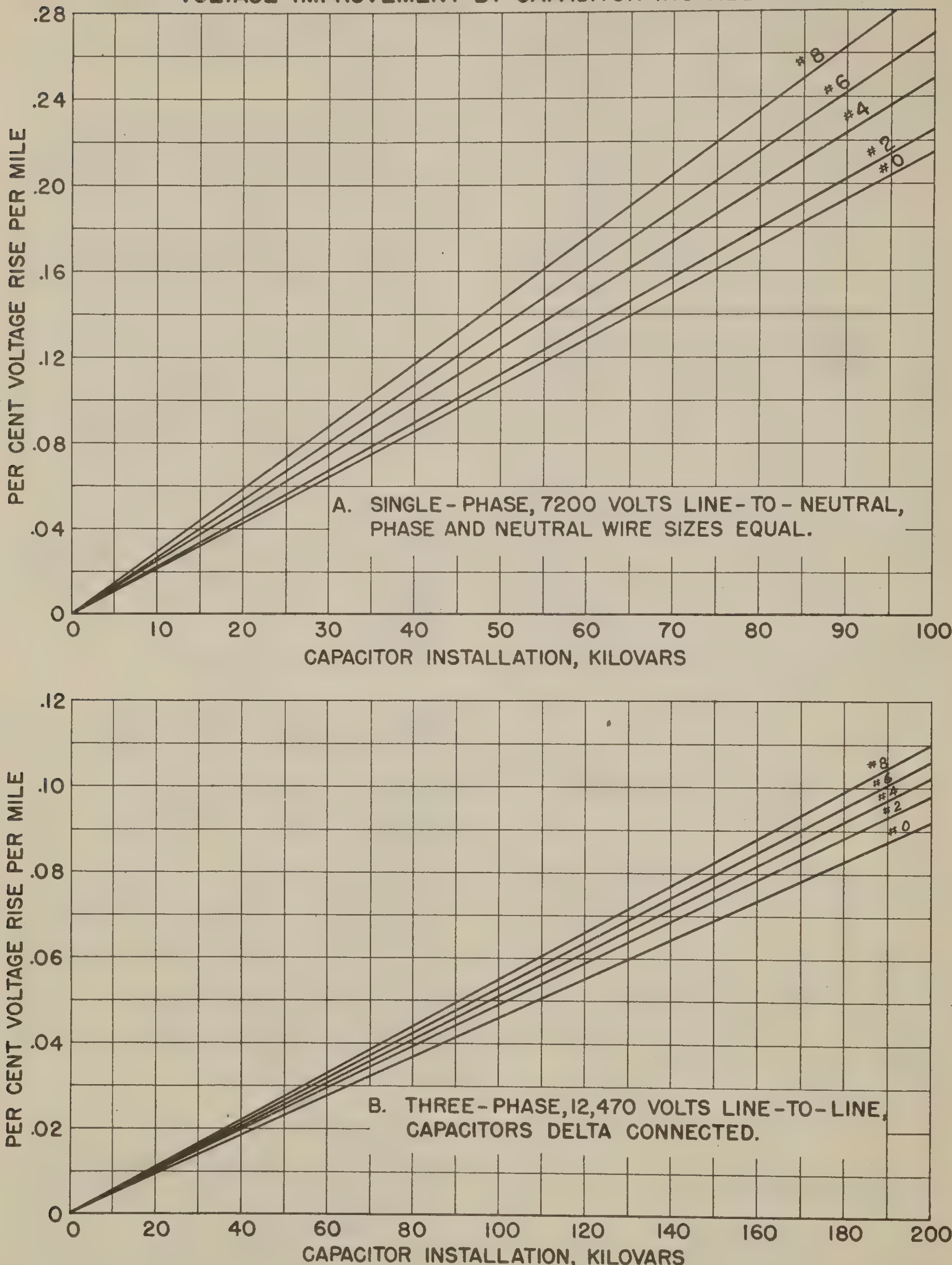
Illustrations of the use of the above equations are given in section III of this manual.

Actually the reactance component of the transformer impedance determines the rise; however, the impedance of most substation transformers is practically equal to the reactance. The percent impedance given on the transformer nameplate can be used without appreciable error.

After capacitors are installed, the voltage rise in the substation transformers, which is a fixed rise, is added to the voltage on the load side of the transformers. When there are no regulators installed at the substation, the voltage rise in the substation transformers

FIGURE 7

VOLTAGE IMPROVEMENT BY CAPACITOR INSTALLATION



would be added to the rise in the distribution line to determine the total effect on the voltage in the distribution line. The voltage rise in a regulated substation is neutralized, if within the operating range of the regulators; if the regulator input voltage is such that it forces the regulator to either the upper or lower limits, the voltage rise within the substation transformers would appear on the distribution line.

The voltage rise in the distribution line or substation transformers, due to capacitors connected in the system, is not dependent on the load. The benefits from this rise on a typical distribution system are usually less important than those from the reduction in system energy losses and the release of kilovolt-ampere capacity for additional useful load.

3. Transmission Line and Other Substation Voltages.

In addition to the rise in feeder voltage due to a capacitor installation, the transmission circuit, as well as other substation transformers between the generating station and the capacitor location, will undergo a voltage rise. Since the electrical characteristics of these parts of the system vary so widely with construction practices among power suppliers, their voltage rise cannot be readily reduced to chart form.

4. Increase in Substation Capacity

Since an increase in power factor reduces the current drawn by a given kilowatt load, a capacitor installation reduces the kva demand. The decrease in load demand due to a capacitor installation corresponds to released substation capacity. This released capacity is of particular value when the substation load approaches the substation capability. Also, capacitors may relieve an existing overloaded condition. The equation for substation capacity released by the installation of capacitors is as follows:

$$T = \text{tkva}\left[\left(\frac{\text{ckvar}}{\text{tkva}}\sin\theta - 1\right) + \sqrt{1 - \frac{\text{ckvar}^2}{\text{tkva}^2}\cos^2\theta}\right]$$

where T = released substation kva
ckvar = capacitor kva
tkva = substation kva rating
θ = original power factor angle

Figure 8 shows the percent substation capacity released for ratios of capacitor kilovars to substation rating at various power factors. The solid curves indicate original peak power factors; the dotted curves indicate power factors after capacitors have been installed. To illustrate the use of the chart, it is assumed that a system with a peak power factor of 0.90 has a load factor such that capacitors with total kilovar rating equal to 20 percent of the substation rating can be installed. Reading vertically from the bottom of the graph at 20 to the original system power factor (0.90) at peak, the percent substation capacity released is shown on the left. This is indicated as seven percent. The power factor now existing at peak load coincides with the intersection of the 20-percent line and the original power factor line; it can be determined by use of the dotted curves. In this example the peak power factor after the capacitors have been installed is 0.97.

## G. LIMITATIONS

1. Harmonics

In determining the actual operating kilovars of capacitors the product of line voltage and current measured by commercial instruments may not indicate the actual operating kilovars. This is due to the deviation of the voltage from a sine wave. In order to determine the actual kilovars at which the capacitor is operating it would be necessary to calculate the kilovars separately for each harmonic and add these values to obtain the total.

The harmonics most often present are the third and fifth. When the operating voltage is 105 percent and the third harmonic is present, the total current may

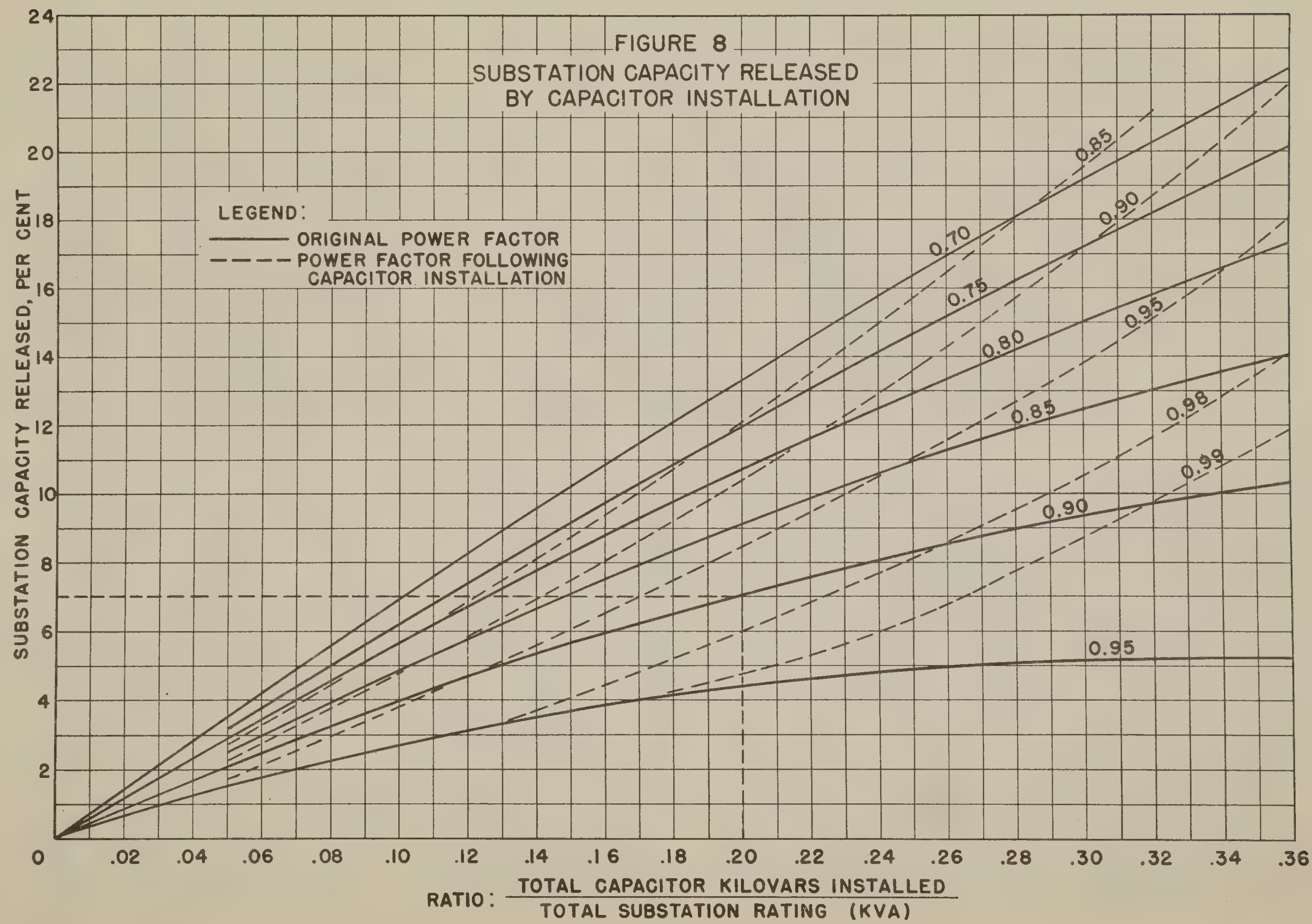


FIGURE 8
SUBSTATION CAPACITY RELEASED
BY CAPACITOR INSTALLATION
LEGEND:
ORIGINAL POWER FACTOR
POWER FACTOR FOLLOWING
CAPACITOR INSTALLATION
0.70
0.75
0.80
0.85
0.90
0.95
0.85
0.90
0.95
0.98
0.99
SUBSTATION CAPACITY RELEASED, PER CENT
0
2
4
6
8
10
12
14
16
18
20
22
24
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
.32
.34
.36
RATIO: TOTAL CAPACITOR KILOVARS INSTALLED / TOTAL SUBSTATION RATING (KVA)

reach 145 percent of normal before the 135 percent thermal limit of a capacitor is exceeded. When the fifth harmonic is present the total current may reach 160 percent of normal before the 135 percent thermal limit is exceeded.

It is seldom that harmonic currents interfere with the use of shunt capacitors. Generally their possible presence is ignored, the capacitors are installed where needed, and corrective steps are taken only if trouble occurs.

Where the wave form is known to be bad particular attention must be given to (1) the location of the capacitor units on the system and (2) the size of the installation for a given location. When a capacitor installation becomes overloaded by harmonic currents the overload can be reduced by changing the size of the installation or relocating the capacitors to add impedance to the flow of harmonic currents.

Occasionally shunt capacitors provide low-impedance paths to voltages from phase wire to neutral that exist on the system. This increases the flow of harmonic currents, with possible interference on communication circuits in the vicinity. The degree of interference depends on the source of the harmonics.

If the source is an over-excited distribution transformer at which a capacitor is installed, the capacitor would act to absorb the harmonic currents, reducing their flow into the line. If the source is at the substation, the capacitors would draw harmonic current through the line. In the latter case, resonance with line and transformer reactance--or an approach to resonance -- may occur at times, especially with large concentrated loads. This condition may occur at frequencies as low as the third and fifth harmonics; it is not necessarily limited to the upper harmonics.

In 3-phase feeders, balancing capacitor kilovars among the phases reduces non-triple harmonic currents (fifth, seventh, eleventh, thirteenth, and higher) in the neutral; it does not reduce odd-triple harmonic currents (third, ninth, fifteenth and higher). In joint-use lines, harmonic currents in the neutral, as well as in the ground, will cause interference. At roadway and wider separations, it is principally the harmonic currents in the ground that produce noise. The currents flow into the ground from the neutral via the neutral ground connections.

In addition to changing size or location of capacitors to eliminate interference problems, the following remedial measures are listed:

a. Install gaps between the neutral connection of 3-phase capacitor banks and ground to reduce the flow of neutral and ground return currents.

b. Install wave traps or filters to block residual harmonic currents.

c. Apply the necessary corrective measures to the communication circuits involved to minimize their susceptibility to inductive interference.

2. Effect on System Stability

Shunt capacitors, especially when applied on rural distribution systems, seldom affect system stability. System stability is of direct concern to distribution system operators only when they operate generating plants. Capacitors reduce the excitation required on the system generators, which in turn lowers the stability margin. This may occur in a period of light load where large numbers of capacitors have been added to the system. The operation of machines up to 95-98 percent lagging power factor usually does not result in serious instability, although under some conditions a lower power factor may be necessary for stable operation.

When shunt capacitors disclose a stability problem, other problems such as high voltage on station buses or circuits usually will be present. The solving of

these other problems will usually correct the stability problem.

## H. INCREASE IN REVENUE

### 1. Feeder Voltage

An increase in kilowatt-hour revenue can be expected with an increase in voltage at the consumer's premises. The wattage requirement of a gas-filled incandescent lamp varies approximately as the three-halves power of the voltage. A rise in feeder voltage would cause no increase in the energy consumption by automatic equipment, and very little by motors as these loads are self-regulating in their energy requirements. A consumer with a 100-percent lighting load would experience a much greater increase in energy consumption than would a consumer having a load consisting largely of motors and automatically controlled resistance loads. To calculate the difference in energy consumption resulting from different voltages at the consumer's premises, a reasonably accurate knowledge of the energy requirements of the lighting, motor and resistance loads would be necessary

To estimate the increase in revenue due to an increase in voltage on the feeder, the average voltage rise must be used. This is done by determining the voltage rise for the feeder by sections, multiplying by the consumers in the respective sections, and dividing the total of these products by the total number of consumers on the feeder.

### 2. Annual Savings in Energy Losses

Figures 9, 10 and 11 are loss charts that can be used to determine the losses caused by the reactive component of the load and the annual savings resulting from the reduction of this part of the load due to the installation of capacitors. To effect the greatest reduction in energy, the capacitor installation should be located at the reactive load center of the distributed load. This is generally coincident with the kilowatt load center and is from one-half to two-thirds of the total length of the feeder from the substation.

To use one of the loss charts a horizontal projection is made from the kilovar (right hand) scale to the load factor line. From this intersection a vertical projection is made to the appropriate conductor line, at which point the annual energy loss per mile is indicated on the left hand scale. Projecting to the right from this point to the appropriate loss energy cost line, a point is determined where the monetary loss per year can be read on the bottom scale.

To illustrate the use of these charts, assume a demand of 130 kvar, at a load factor of 0.60, on a single-phase No. 6 line. On figure 9 the annual energy loss is indicated as 2,750 kwh; at a cost of 1.2 cents per kilowatt-hour, the monetary loss is $33.00 per year.

Correct results will not be obtained by use of the loss charts, if the power factor becomes leading. If the size of the capacitor installation is equal to the light-load kilovar demand, the line loss due to the light-load kilovar load is not thereby reduced to zero, but to a small percentage of the value without capacitors.

To determine the load center of a distributed load either of the two following methods may be employed:

(a) Multiply the kilovolt-ampere value of the individual loads on the feeder by their respective distances from the substation, find the total of these products and divide by the total kilovolt-ampere load on the feeder (this method is illustrated in section IV), or

(b) Locate the point on the feeder where the current is one-half the total current into the feeder at the sending end.

## FIGURE 9

### SINGLE-PHASE CONDUCTOR $I^2R$ LOSS DUE TO REACTIVE COMPONENT

7.2/12.5 KV SYSTEM WITH MULTIGROUNDED NEUTRAL

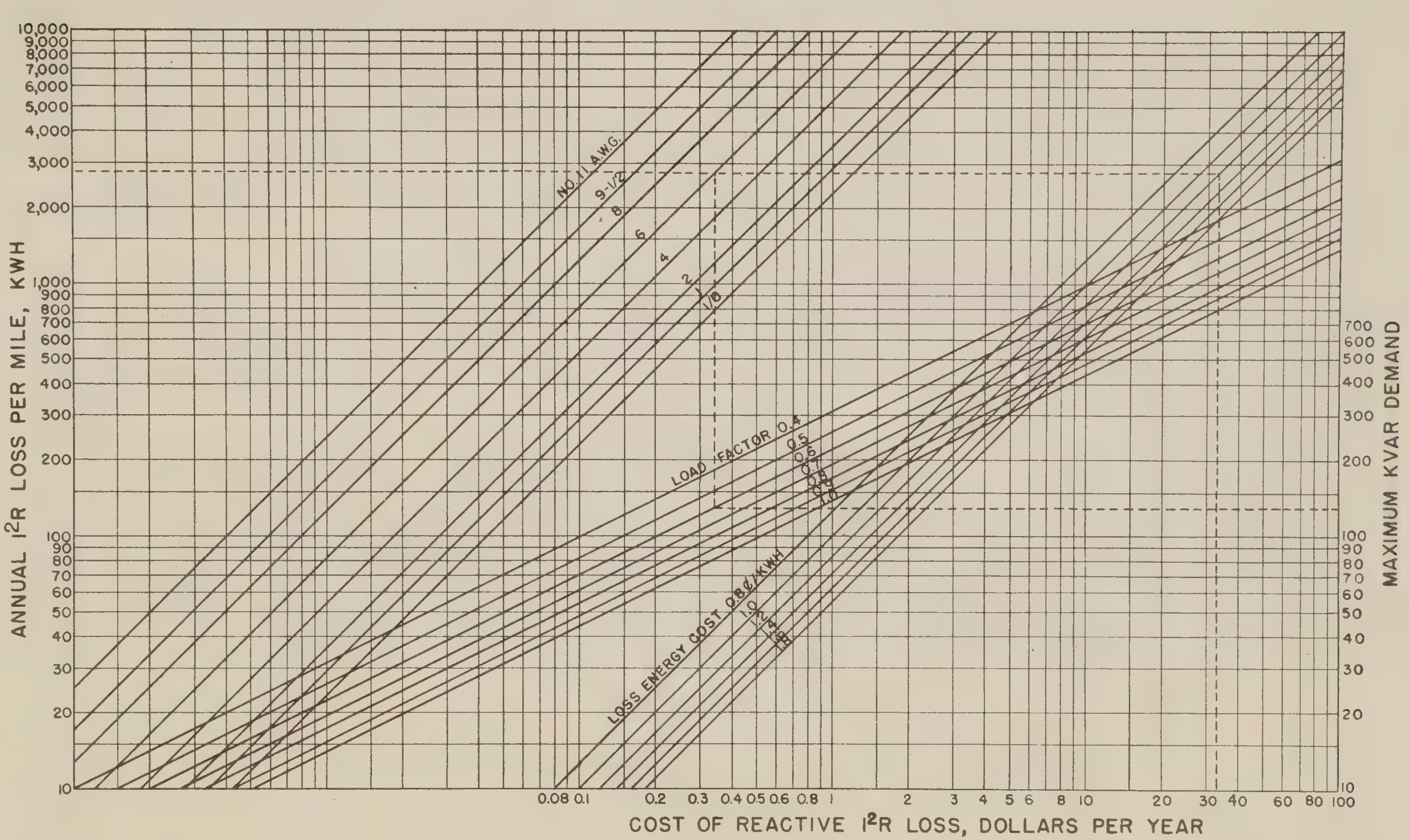


FIGURE 10

'V' PHASE CONDUCTOR $I^2R$ LOSS DUE TO REACTIVE COMPONENT

7.2/12.5 KV SYSTEM WITH MULTIGROUNDED NEUTRAL

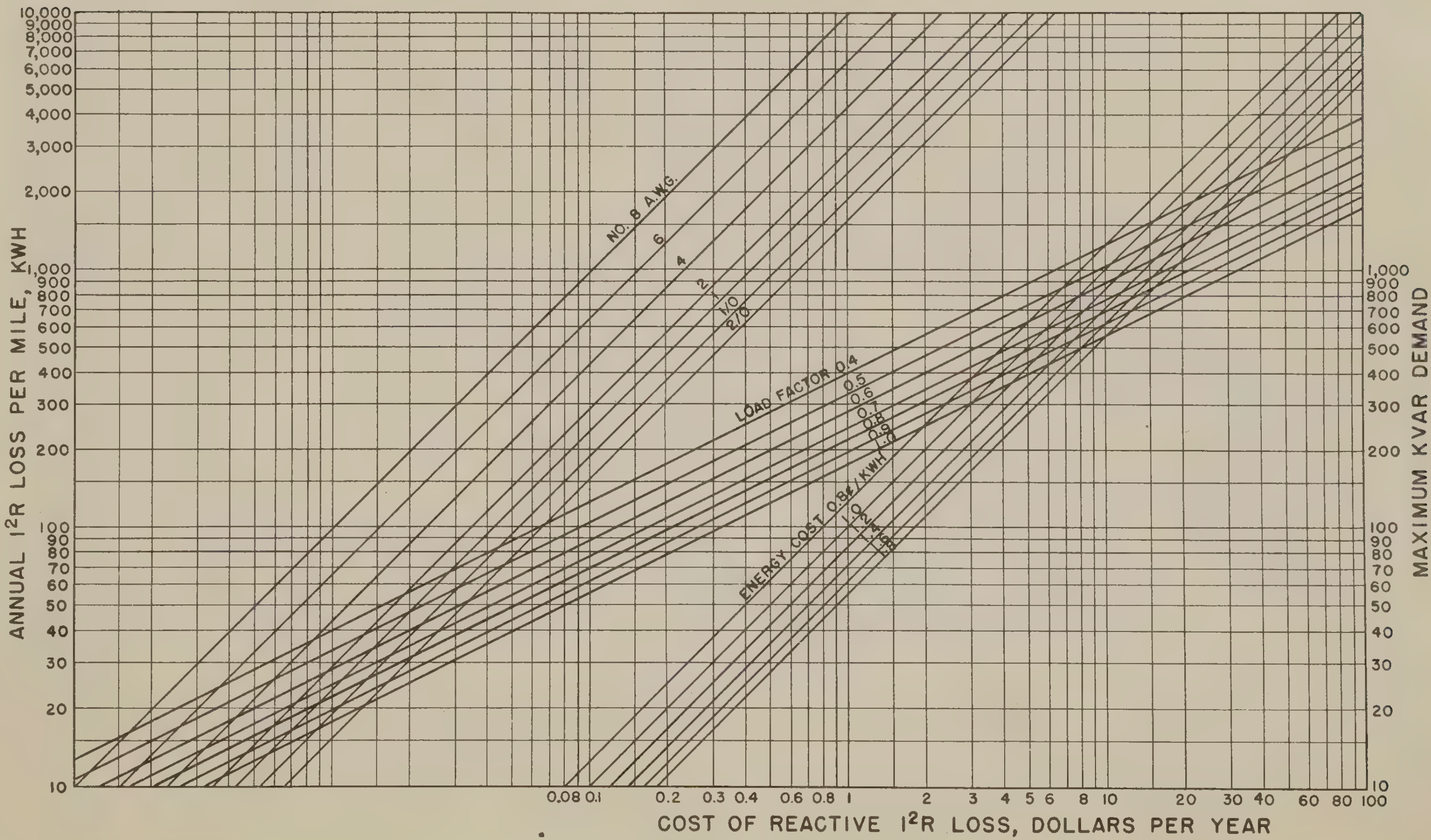
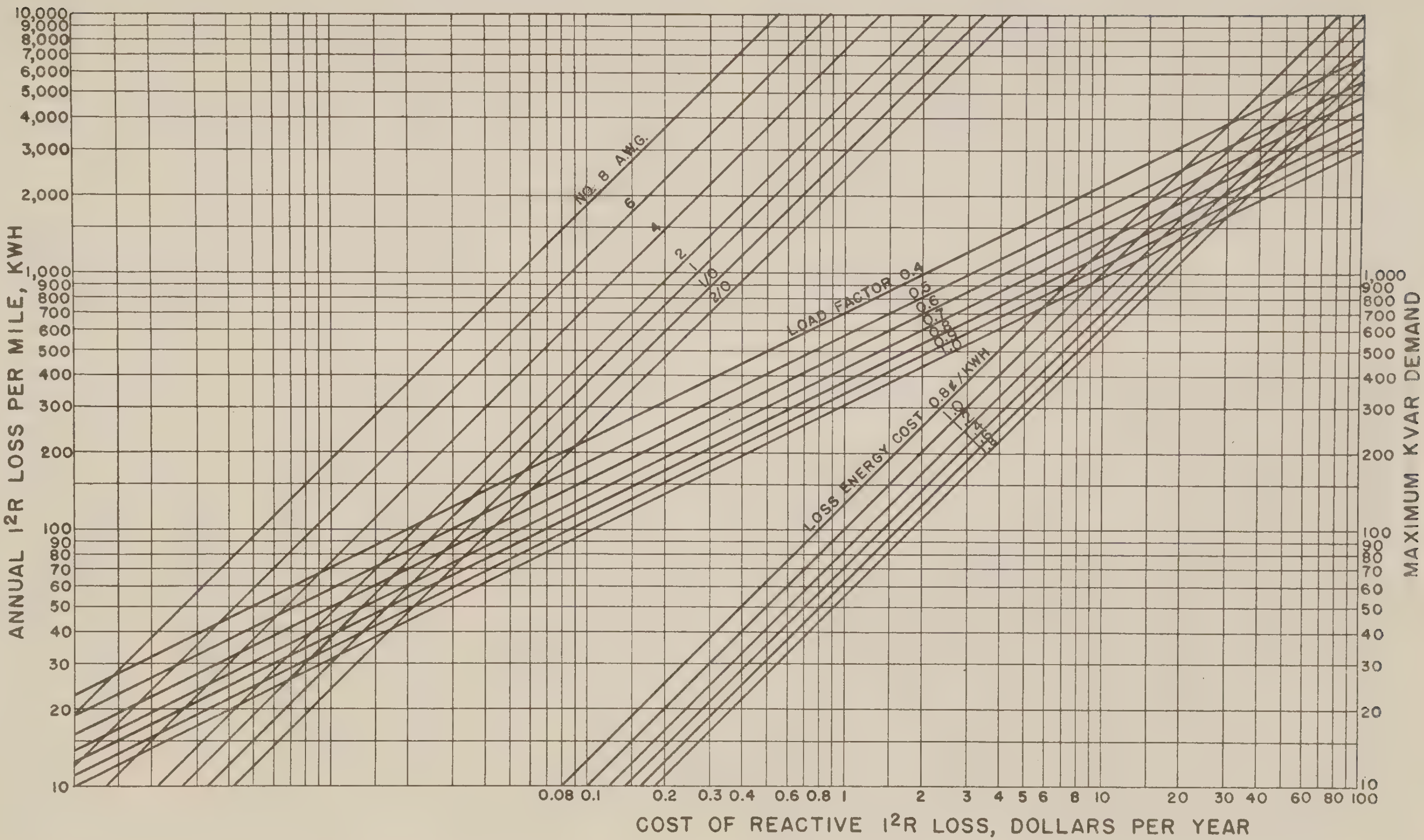


FIGURE 11

THREE-PHASE CONDUCTOR $I^2R$ LOSS DUE TO REACTIVE COMPONENT

7.2/12.5 KV SYSTEM WITH MULTIGROUNDED NEUTRAL



3. Savings in Power Factor Penalties.

Two types of power factor penalty clauses are generally used by power suppliers. One type of clause exists where the billed demand is equal to the measured peak demand multiplied by the ratio of a specified power factor, usually 0.85, to the measured power factor at the measured peak demand. Some contracts allow no credit for power factors above 0.85 by exercising this clause only if the peak power factor is below 0.85. Other contracts allow the use of the clause both ways, to provide a reduction in the demand charge for higher power factor. Where credit for good power factor can be claimed, the power factor can be computed and the savings in energy cost due to a capacitor installation estimated by computing the reactive component of demand at peak load, subtracting the kilovolt-ampere rating of the capacitor installation, and computing the new power factor. The reactive component can be computed by the use of table I. By using the same kilowatt demand figure in each case, the new kilovolt-amperes can be calculated.

The above type of power factor penalty clause has usually caused little concern because the characteristics of the rural load (often 0.90 to 0.95 power factor at peak) do not often result in penalties and, as shown, may provide benefits in some instances.

To illustrate the use of table I, a peak demand of 1,250 kilovolt-amperes is assumed, at a power factor of 0.80. The power factor angle for this power factor is 37 degrees; column B indicates sin θ as 0.60. The components of the peak demand are as follows:

In-phase component
1,250 X 0.80 = 1,000 kw.

Reactive component
1,250 X 0.60 = 750 kvar.

If capacitors totaling 200 kvar were installed, the remaining reactive load would be 750 kvar minus 200 kvar or 550 kvar. Tangent of θ, the power factor angle, would then be 550/1,000 or 0.55. Referring to columns A and C in table I, this value would correspond to a new power factor of 0.875. In this case interpolation is necessary.

The second type of power factor penalty clause is peculiar to at least one power supplier and its subsidiaries. This is based upon the average power factor, which is derived from the readings of a kilowatt-hour meter and a kilovar-hour meter. Dividing kilovar-hours by kilowatt-hours gives the tangent of the average power factor angle. The corresponding cosine of the angle, or power factor, can be found by reference to table I. The average power factor thus determined is a mathematical concept and indicates neither the maximum nor the minimum power factor encountered. It cannot be used to determine the amount of power factor correction required.

Since the kilovar load on the rural system at the minimum load point is a 24-hour load, the installation of capacitors for this minimum load can effect a substantial reduction in demand charges.

Table I

Power Factor Table

| A POWER FACTOR (COS θ) | POWER FACTOR ANGLE (θ) (TO NEAREST DEGREE) | B (SIN θ) | C (TAN θ) |
|---|---|---|---|
| .40 | 66 degrees | .92 | 2.29 |
| .45 | 63 | .89 | 1.98 |
| .50 | 60 | .87 | 1.73 |
| .55 | 57 | .84 | 1.52 |
| .60 | 53 | .80 | 1.33 |
| .65 | 49 | .76 | 1.17 |
| .70 | 45 | .71 | 1.02 |
| .75 | 41 | .66 | .88 |
| .80 | 37 | .60 | .75 |
| .85 | 32 | .53 | .62 |
| .90 | 26 | .44 | .48 |
| .95 | 18 | .31 | .33 |
| 1.00 | 0 | .00 | .00 |

To compute the new power factor, multiply the kilovar rating of the capacitor installation by 730, the number of hours in a month, and subtract the product from the original kilovar-hour meter reading. The new power factor is then computed in the same manner as before. The demand penalty is usually stated in the same manner as in the first case, but since this clause is applicable whether the power factor is higher or lower than that specified in the penalty clause, appreciable savings are possible in demand charges. Rural systems with peak power factors of 0.90 show these average values from 0.75 to 0.80, which results in high energy costs where this type of power factor clause is in effect. This average power factor should not be used to estimate the size of capacitor installations and should not be confused with power factor at peak or at any other specified point on the load curve of the system. It merely involves the total kilovar-hours delivered by the supplier during a specified period of time, measured in the same manner as the kilowatt-hours delivered during the same period.

To illustrate the use of table I in computing average power factor, it is assumed that, before installation of capacitors, readings of 410,000 kilowatt-hours and 341,000 kilovar-hours were obtained. Tangent of $\theta$ would be equal to 341,000/410,000 or 0.83. Column A of table I indicates the corresponding average power factor as 0.77. If 200 kilovars of capacitors were installed, the decrease in kilovar-hours per month would be 730 X 200 or 146,000 kilovar-hours. The kilovar-hours recorded would then be 341,000 minus 146,000 or 195,000 kilovar-hours. Tangent of $\theta$, the new power factor angle, would be 195,000/410,000 or 0.48. Again referring to column A of table I, the corresponding average power factor is indicated as 0.90.

## A. ASSUMED ORIGINAL CONDITIONS

The effect of reactive load factor is illustrated in the following example. A system has a main substation rated at 1,500 kva. Its peak demand was originally computed at 1,482 kva which was three times the kilovolt-amperes per main feeder; three such feeders carry the load from the substation. The substation is assumed to be equipped with voltage regulators.

A 200-kwh consumption per consumer per month at a peak load power factor of 0.90 was used as the basis for design of substation and conductors. At present the energy consumption is 225 kwh per month per consumer at a peak load power factor of 0.85. Figure 12 shows one of the 3-phase feeders; the other two are similar. Table II indicates the design load on various sections of the feeder being considered, including the load on one single-phase branch to the end.

Table III indicates the increased load and the resulting overload on the substation from this feeder. The peak load on the feeder is now 485 kw or 571 kva; this results in a substation peak load of 1455 kw or 1713 kva. The increased voltage drop is also indicated. A similar overload on the other two feeders is assumed. At present the power factor at minimum load is assumed to be 0.70 and the reactive load factor, 0.70. The minimum kilowatt demand is assumed to be one-fifth the peak kilowatt demand. Since kilowatts and kilovars are equal at minimum load, the minimum reactive load is one-fifth the peak kilowatt demand. This relation is used to determine the capacitor kilovar installation.

## B. CAPACITOR LOCATION

Since the minimum kilovar demand is all that can be satisfactorily corrected by unswitched capacitors, a 15-kvar capacitor would be installed. Table III

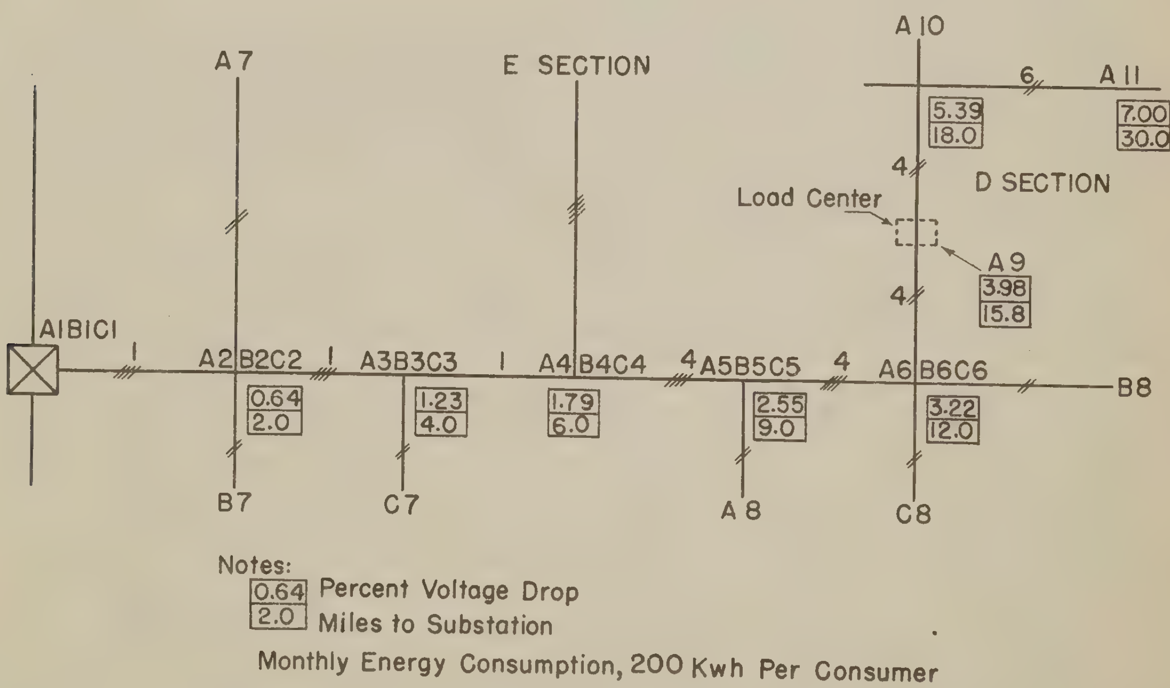



Figure 12. Circuit diagram for voltage drop calculation

## Table II

### Voltage Drop Calculation
### Monthly Energy Consumption, 200 kwh Per Consumer
### Power Factor 0.90

| SECTION | CONSUMERS | | | KW PEAK | SECTION LENGTH, MI. | KW X MI. | WIRE SIZE | NUMBER OF PHASES | WIRE FACTOR | VOLTAGE DROP, PERCENT |
|---|---|---|---|---|---|---|---|---|---|---|
| | ULTIMATE | BEYOND THIS POINT | EQUIVALENT | | | | | | | |
| A11 - A10 | 33 | 0 | 17 | 20 | 12 | 240 | 6 | 1 | 6.70 | 1.61 |
| At A10 | 37 | | | | | | | | | |
| A10 - A9 | 7 | 70 | 74 | 71 | 2.2 | 156 | 4 | 1 | 4.83 | .76 |
| A9 - A6 B6 C6 | 13 | 77 | 84 | 79 | 3.8 | 300 | 4 | 1 | 4.83 | 1.45 |
| At A6 B6 C6 | 150 | | | | | | | | | |
| A6 B6 C6-A5 B5 C5 | 16 | 232 | 240 | 185 | 3 | 555 | 4 | 3 | 1.20 | .67 |
| At A5 B5 C5 | 20 | | | | | | | | | |
| A5 B5 C5 - A4 B4 C4 | 16 | 268 | 276 | 210 | 3 | 630 | 4 | 3 | 1.20 | .76 |
| At A4 B4 C4 | 275 | | | | | | | | | |
| A4 B4 C4 - A3 B3 C3 | 16 | 559 | 567 | 390 | 2 | 780 | 1 | 3 | .715 | .56 |
| At A3 B3 C3 | 15 | | | | | | | | | |
| A3 B3 C3 - A2 B2 C2 | 15 | 590 | 598 | 410 | 2 | 820 | 1 | 3 | .715 | .59 |
| At A2 B2 C2 | 40 | | | | | | | | | |
| A2 B2 C2 - A1 B1 C1 | 15 | 645 | 653 | 445 | 2 | 890 | 1 | 3 | .715 | .64 |

Notes:

1. Wire Factor (single-phase) = $\frac{(R \cos \Theta + X \sin \Theta)\ 105}{.96 \times \cos \Theta \times kv^2}$

2. Wire factor (three-phase) = $\frac{(R \cos \Theta + X \sin \Theta)\ 100}{.96 \times \cos \Theta \times kv^2 \times 3}$

where R = resistance, ohms per mile
X = reactance, ohms per mile
$\Theta$ = power factor angle, degrees
kv = phase voltage, kilovolts

3. These wire factors are applicable to this table and to table III.

4. Explanation of method of calculation is given in reference 7,

Table III

Voltage Drop Calculation
Monthly Energy Consumption, 225 kwh Per Consumer
Power Factor 0.85

| SECTION | EQUIVALENT CONSUMERS | PEAK KW | MINIMUM KW | SECTION LENGTH, MI. | PEAK KW X MI. | WIRE FACTOR | VOLTAGE DROP, PERCENT |
|---|---|---|---|---|---|---|---|
| A11 - A10 | 17 | 24 | 4.8 | 12 | 288 | 6.98 | 2.01 |
| A10 - A9 | 74 | 78 | 15.6 | 2.2 | 172 | 5.11 | .88 |
| A9 - A6 B6 C6 | 84 | 86 | 17.2 | 3.8 | 327 | 5.11 | 1.67 |
| A6 B6 C6 - A5 B5 C5 | 240 | 203 | 40.6 | 3 | 609 | 1.25 | .76 |
| A5 B5 C5 - A4 B4 C4 | 276 | 227 | 45.4 | 3 | 681 | 1.25 | .85 |
| A4 B4 C4 - A3 B3 C3 | 567 | 423 | 80.5 | 2 | 846 | .778 | .66 |
| A3 B3 C3 - A2 B2 C2 | 598 | 450 | 90.0 | 2 | 900 | .778 | .70 |
| A2 B2 C2 - A1 B1 C1 | 653 | 485 | 97.0 | 2 | 970 | .778 | .76 |

indicates the minimum load at this point. The kilovar load center is found to be 15.8 miles from the substation, as indicated in Table IV. This distance is based on the assumption that all consumers impose equal loads on the system. In an actual case the total of transformer ratings in each section may be used. Weighting is necessary to properly relate the effects of this capacitor to those of the capacitors on the other two phases of this feeder.

The location of the capacitor at the load center of the phase under consideration affords the maximum reduction in feeder loss. Location at a greater distance from the substation, even at the end of the single-phase branch, would result in a greater voltage rise. However, the greater improvement in voltage correction would be attained at a higher feeder loss. For the sake of brevity this illustration deals only with a capacitor on one phase. It is assumed that the total feeder load is balanced on the three phases and that each of the other two single phases beyond A6 B6 C6 requires a 15-kvar capacitor located by the same method.

## C. EFFECT ON VOLTAGE

Line voltage rise from substation to capacitor would be

$$\text{A1B1C1-A2B2C2:-}\ \frac{90 \times 1.49}{10 \times (12.47)2} = 0.09\%$$

$$\text{A2B2C2-A3B3C3:-}\qquad 0.09$$

$$\text{A3B3C3-A4B4C4:-}\qquad 0.09$$

$$\text{A4B4C4-A5B5C5:-}\ \frac{45 \times 2.39}{10 \times (12.47)2} = 0.07$$

$$\text{A5B5C5-A6B6C6:-}\qquad 0.07$$

$$\text{A6B6C6-A9:}\ -\ \frac{15 \times 5.06}{10 \times (7.2)2} = 0.15$$

$$\text{Total, A1B1C1 - A9}\qquad 0.56\%$$

At an assumed transformer impedance of seven percent and a total of 270 kvar of capacitors, the percent voltage rise in the substation transformers would be

$$\frac{270}{1,500} \times 7.0 = 1.26\%$$

In the event that there were no voltage regulators at the substation, the total voltage rise from substation transformer primary windings to the capacitor location would be the sum of the rise in the transformers plus that in the feeder from substation to capacitor. This rise would be 1.82 percent. Tables II and III indicate that the 25-kwh increase in load per consumer per month, together with a decline in power factor, increased the voltage drop to the end of the line by 1.25 percent. The capacitors on the system decreased the voltage drop to the

## Table IV

### Location of Load Center
### D Section

| | CONSUMERS | MILES FROM SUBSTATION | PRODUCT |
|---|---|---|---|
| Section A1B1C1-A4B4C4 (One half of total load is assumed to be on this section.) | | | |
| A1B1C1-A2B2C2 | 7.5 | 1 | 7.5 |
| At A2B2C2 | 20 | 2 | 40.0 |
| A2B2C2-A3B3C3 | 7.5 | 3 | 22.5 |
| At A3B3C3 | 7.5 | 4 | 30.0 |
| A3B3C3-A4B4C4 | 8 | 5 | 40.0 |
| Total | 50.5 | - | 140.0 |
| Single-phase equivalent | 16.8 | - | 46.7 |
| Section A4B4C4-A6B6C6 | | | |
| A4B4C4-A5B5C5 | 16 | 7.5 | 120.0 |
| At A5B5C5 | 20 | 9 | 180.0 |
| A5B5C5-A6B6C6 | 16 | 10.5 | 168.0 |
| Total | 52 | - | 468.0 |
| Single-phase equivalent | 17.3 | - | 156.0 |
| Section A6B6C6-A11 | | | |
| A6B6C6-A10 | 20 | 15 | 300.0 |
| At A10 | 37 | 18 | 666.0 |
| A10-A11 | 33 | 24 | 792.0 |
| Total | 90 | - | 1758.0 |
| Computation of load center | | | |
| A1B1C1-A4B4C4 | 16.8 | - | 46.7 |
| A4B4C4-A6B6C6 | 17.3 | - | 156.0 |
| A6B6C6-A11 | 90.0 | - | 1758.0 |
| Total | 124.1 | - | 1960.7 |

Distance from substation to load center 1960.7/124.1 = 15.8 mi.

Table V

Annual kwh Loss in Feeder Due to kvar Load
Monthly Energy Consumption, 225 kwh Per Consumer

| SECTION | NO. OF PHASES | WIRE SIZE | NO CAPACITORS REACTIVE LOAD FACTOR = 0.70 | | | WITH CAPACITORS | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | PEAK KVAR LOAD | TOTAL KWH LOSS | KWH LOSS PER PHASE | PEAK KVAR LOAD | LOAD FACTOR | TOTAL KWH LOSS | KWH LOSS PER PHASE |
| A11 - A10 | 1 | 6 | 15 | 611 | 611 | 15 | .70 | 611 | 611 |
| A10 - A9 | 1 | 4 | 48 | 693 | 693 | 48 | .70 | 693 | 693 |
| A9 - A6B6C6 | 1 | 4 | 53 | 1482 | 1482 | 38 | .58 | 874 | 874 |
| A6B6C6 - A5B5C5 | 3 | 4 | 126 | 1860 | 620 | 81 | .54 | 519 | 173 |
| A5B5C5 - A4B4C4 | 3 | 4 | 141 | 2400 | 800 | 96 | .56 | 750 | 250 |
| A4B4C4 - A3B3C3 | 3 | 1 | 263 | 2800 | 467 | 173 | .54 | 800 | 133 |
| A3B3C3 - A2B2C2 | 3 | 1 | 279 | 3200 | 533 | 189 | .56 | 1040 | 140 |
| A2B2C2 - A1B1C1 | 3 | 1 | 301 | 3660 | 610 | 211 | .57 | 1320 | 220 |
| | | | | Total ........ | 5816 kwh | | | Total ......... | 3094 kwh |

Reduction in energy loss = 5816 -3094 = 2722 kwh.

end of the line to a value less than the design value.

Since the capacitor location at A9 is the load center, the average voltage rise on this particular feeder is equal to the above value of 0.56 percent. Therefore, the average voltage rise in the feeder, including the rise in substation transformers, if there were no substation regulators, would be 1.82 percent.

## D. ECONOMIC CONSIDERATIONS

### 1. Energy Saving in Line Losses.

Table V indicates energy losses for design and present loads. Subtracting line loss due to reactive kilovar load, with the 15-kvar capacitor installed, from line loss without the capacitor, it is seen that the capacitor effects a saving of 2722 kwh per year. At an energy cost of one cent per kilowatt-hour, this would amount to $27.22.

### 2. Substation Capacity Released.

With a total of 270 kvar of capacitors installed at 18 locations on the three feeders from the substation, the released substation capacity is determined from figure 8. With the ratio of 270 to 1,500 or 0.18, and the present power factor of 0.85 without capacitors, the released substation capacity is indicated as 8-1/3 percent, which is equal to 125 kva. Since tables II and III indicate a decrease of 126 kva in substation load, this value will be allowed in subsequent calculations.

In order to determine the value per kilovolt-ampere of released substation capacity, it is necessary to know the conditions applicable to an individual power system. Some factors involved in an estimate of the value of the released kilovolt-amperes are the following:

(a) Original cost and present value of the substation equipment that would need to be replaced, if capacitors were not used.

(b) Cost of new equipment to provide the above additional substation capacity.

(c) Future date when additional substation load capacity would be necessary, due to continued load growth.

For calculating approximate savings, it is assumed that the released substation capacity is worth $20 per kva and that the annual rate of capitalization is four percent. The 270 kva of capacitors would result in an annual saving of 126 X $20 X 0.04 = 100.80. The amount to be ascribed to each of the 18 capacitors per year would be $5.60.

### 3. Increase in Energy Consumption.

Table VI indicates the effect of increased voltage on annual energy consumption for three types of loads. The figure shows estimated increase in energy consumption with and without substation voltage regulators. The annual energy consumption by the 108 consumers affected by the 15-kvar capacitor is assumed to be 12 X 108 X 225 or 291,600 kwh. A base voltage of 120 volts is assumed to have existed at the beginning of the feeder, prior to capacitor installation; the average voltage on the feeder at that time was 117 volts.

The increase in energy consumption would be reflected in a slightly higher net return from the power system. However, it is difficult to assign a monetary value per kilowatt-hour to determine the actual net return.

### 4. Saving in Demand Charge.

As previously discussed, any saving in demand charge by the power supplier depends on the contract in effect. The following illustration is for the average power factor type of contract, which is based on hours use of maximum demand as follows:

First 200 hr use maximum kva at $.01 per kilowatt-hour.

Table VI

Increase in Annual Energy Consumption on Feeder with 15-kvar Capacitor Installation

| LOAD | | | REGULATED BUS 0.5% VOLTAGE INCREASE | UNREGULATED BUS 1.9% VOLTAGE INCREASE |
|---|---|---|---|---|
| MOTORS | RESISTANCE | LIGHTS | | |
| --- | --- | 100% | 2,330 kwh | 8,750 kwh |
| 41% | 22% | 37% | 870 kwh | 3,780 kwh |
| 40% | 34% | 26% | 580 kwh | 2,620 kwh |

Next 100 hr use maximum kva at $.0075 per kilowatt-hour.

Excess over 300 hr use maximum kva at $.005 per kilowatt-hour.

Prior to installation of capacitors on the system, with maximum demand of 1713 kva on substation and a monthly energy consumption of 3 X 648 X 225 = 437,400 kwh, the monthly charge would have been as follows:

| | | |
|---|---|---|
| 200 X 1,713 = 342,600 at $.01 | = | $3426.00 |
| 94,800 at $.0075 | = | 711.00 |
| 437,400 | | $4136.00 |

After installation of 270 kvar of capacitors on the system, when the peak load on the substation has been reduced to 1,587 kva, the monthly charge is as follows:

| | | |
|---|---|---|
| 200 X 1,587 = 317,400 at $.01 | = | $3174.00 |
| 120,000 at $.0075 | = | 900.00 |
| 437,400 | | $4074.00 |

The saving per year that could be ascribed to any one of the 18 15-kvar capacitors would be

$$\frac{(4,136 - 4,074) \times 12}{18} = \$41.33$$

5. Recapitulation.

The cost of a 15-kvar capacitor installation on an existing single-phase line pole is approximately $175. If it is assumed that the above power contract applies, the savings to be ascribed to a 15-kvar capacitor installation would be as follows:

| | |
|---|---|
| Line losses ................. | $27.22 |
| Released substation capacity ... | 5.60 |
| Demand charge ............... | 41.33 |
| Total............. | $74.15 |

These savings would pay for the capacitor in less than three years.

If no saving in demand charge is effected by a capacitor installation, the savings in line losses and released substation capacity would pay for the capacitors in approximately five years.

It is to be noted that this illustration involves the most expensive type of capacitor installation. The cost per kvar of a 15-kvar unit is approximately 30 percent more than a 25-kvar unit. Exclusive of cost of capacitor units, the cost of a single-phase capacitor installation is no greater for a 25-kvar capacitor, or larger, than it would be for a 15-kvar capacitor. Therefore, the total installed cost per kvar becomes considerably less as the amount of capacitor kilovars increases.

## INSTALLATION OF CAPACITORS TO CORRECT FOR INDUCTION MOTOR LOADS

Capacitors installed on the primary circuit by the cooperative are in some cases limited to those required for the correction of the power factor of the system without considering the requirements of large inductive loads.

If capacitors are installed on the primary line specifically to correct for large inductive loads, switched capacitors will be necessary and the cost per kilovar will be somewhat higher. The power factor clause in these consumers' contracts should be designed and enforced to take into consideration the cost of kilovars supplied.

Secondary capacitors are available for installation at the motor at costs which compare favorably with primary units. In addition, the benefits of the capacitor at the motor in decreasing starting and running current and the attendant losses are extended to the secondary and service wiring, as well as the supply transformer and the balance of the distribution system.

The motor starter is used to switch the capacitor which is wired directly to the large motor. The resulting load then behaves like a high power factor load on the system.

Certain limitations on the size of capacitor installations for various motor sizes and rotational speeds must be imposed to avoid the possibility of self-excitation of the motor with its attendant problems. The maximum size of capacitor which can be used on an induction motor is one which is not large enough to supply the magnetization current of the motor at any point on its starting and running curve. If this limitation is exceeded, the motor may run at a subsynchronous speed and draw excessive current which may damage the windings.

If the supply switch is opened momentarily, the motor will operate as an induction generator while it is coasting. Reconnection of the motor to the supply will have the same effect as closing the main switch on a generator which is not synchronized to the supply line.

At the instant the motor is disconnected from the supply line, a circuit consisting of the inductance of the motor windings in parallel with a capacitor is set up. Resonance may occur at some point on the motor speed curve as it slows down. If this resonance occurs, a voltage will be built up on the windings which will be limited only by the "Q" of the tuned circuit. The damping effect of the line resistance will no longer limit this voltage and the motor insulation may be punctured.

Table VII is a listing of the maximum permissible capacitor rating which can be used with various motors so that no self excitation voltages will be produced. These values do not necessarily correspond to standard capacitor ratings and in these cases the next lower rating should be used.

When capacitors are connected to motor terminals, the current flowing in the supply circuit is reduced. When the capacitors are connected on the motor side of the overload protective device, this device will no longer give adequate protection if it has been selected on the basis of the uncorrected full load current. The relay or circuit breaker should then be adjusted or a new fuse rating should be selected to operate at a lower current consistent with the reduced line current.

One kilovar of secondary capacitor at the load is equivalent to approximately 1.04 kilovar of primary capacitors from the standpoint of reduction of losses in the

transformer and on the service side of the installation. With this type of capacitor application where the load varies so widely, the secondary capacitor which is switched with the load is a practical and economical solution.

Table VII [8]

Recommended Maximum Capacitor Rating when Capacitor and Motor are Switched as a Unit

| INDUCTION MOTOR HP RATING | 3600 RPM | | 1800 RPM | | 1200 RPM | |
|---|---|---|---|---|---|---|
| | CKVA | % AR | CKVA | % AR | CKVA | % AR |
| 10 | 2.5 | 9 | 4 | 11 | 4 | 12 |
| 15 | 2.5 | 9 | 5 | 11 | 5 | 11 |
| 20 | 5 | 9 | 5 | 10 | 5 | 11 |
| 25 | 5 | 9 | 7.5 | 10 | 7.5 | 10 |
| 30 | 7.5 | 9 | 10 | 9 | 10 | 10 |
| 40 | 10 | 9 | 10 | 9 | 10 | 10 |
| 50 | 12.5 | 9 | 12.5 | 9 | 12.5 | 9 |
| 60 | 15 | 9 | 15 | 8 | 15 | 9 |
| 75 | 17.5 | 9 | 17.5 | 8 | 17.5 | 8 |
| 100 | 22.5 | 9 | 22.5 | 8 | 22.5 | 8 |
| 125 | 25 | 9 | 27.5 | 8 | 27.5 | 8 |
| 150 | 32.5 | 9 | 35 | 8 | 35 | 8 |
| 200 | 42.5 | 9 | 42.5 | 8 | 42.5 | 8 |

| INDUCTION MOTOR HP RATING | 900 RPM | | 720 RPM | | 600 RPM | |
|---|---|---|---|---|---|---|
| | CKVA | % AR | CKVA | % AR | CKVA | % AR |
| 10 | 5 | 17 | 5 | 23 | 7.5 | 28 |
| 15 | 7.5 | 16 | 7.5 | 21 | 10 | 26 |
| 20 | 7.5 | 15 | 10 | 20 | 12.5 | 24 |
| 25 | 10 | 14 | 10 | 19 | 15 | 22 |
| 30 | 10 | 13 | 12.5 | 18 | 15 | 21 |
| 40 | 12.5 | 12 | 15 | 16 | 17.5 | 19 |
| 50 | 15 | 12 | 20 | 15 | 22.5 | 17 |
| 60 | 17.5 | 11 | 22.5 | 14 | 25 | 16 |
| 75 | 20 | 11 | 27.5 | 13 | 30 | 15 |
| 100 | 25 | 10 | 35 | 12 | 37.5 | 14 |
| 125 | 30 | 9 | 40 | 11 | 47.5 | 13 |
| 150 | 37.5 | 9 | 47.5 | 11 | 55 | 13 |
| 200 | 45 | 9 | 60 | 10 | 67.5 | 12 |

When manual reduced-voltage autotransformer type starter is used, motor and load characteristics must be considered, in order to keep mechanical torque in shaft and coupling below six times normal.

Ckva is rated kva of capacitor connected at motor terminals.

Percent AR is percent reduction in line current due to capacitor and is helpful for selecting the proper motor overload setting when overload device carries sum of motor and capacitor currents.

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